



Review Article

Capacity Without Ductility: A Quantitative Synthesis of Flexural Strengthening Evidence for High-Strength Concrete Beams

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Abstract

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While high-strength concrete can increase compressive strength without a corresponding increase in tensile strength, four strategies are used for strengthening concrete: ultra-high-performance concrete (UHPC) overlays, fibre-reinforced polymer (FRP) systems, matrix fibres, and recycled constituents. They are tested separately against their respective controls using different specimen geometries and cannot be compared across published results. This review aims to consolidate 23 studies identified between 2020 and 2026 through a reproducible database search. Results were normalized against the capacity of each study's own control and presented as the capacity gain ratio and ductility retention ratio, as well as in terms of a strength-ductility trade-off index (STI), which is the fractional change in the product of the capacity gain ratio and ductility retention ratio. A capacity gain can be calculated in 13 studies: the range is 26.4% to 36.6%, with a mean of 31.0%, without discriminating between systems. There are only three studies that report both quantities, and the index rearranges these quantities. The hybrid FRP sheets rank 1st for capacity and -0.245 for STI, while stainless reinforcement ranks 1st for STI and -0.750 for capacity, respectively. The fact that the sample is three is the second finding. Fifteen of the 23 studies report ultimate load, six report other outcomes, none report deflection at yield, and four studies report on the interface through which overlay systems transfer their gain. Therefore, a minimum reporting set is suggested. If either deflection at first yield or ultimate load were required, the comparable number of samples would be tripled, and if both deflections were required, it would be tripled again, without casting another specimen.

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I. INTRODUCTION

In common usage, high-strength concrete (HSC) is considered to have a compressive strength exceeding 40 MPa, with recent mixes achieving 100 MPa and higher through the use of low water-cement ratios, well-graded aggregates, and silica fume, fly ash, or slag. This strength is also achieved by a high-density microstructure that makes the material more impermeable, improves resistance to chloride penetration and sulfate attack compared with ordinary concrete, and maintains a high stiffness level after repeated freeze-thaw cycles [1]. The tensile capability does not increase by the same amount. HSC beams fail at loads near those of normal-strength beams and with very little

deformation; thus, they are not allowed to be used where energy absorption is important [2], [3].

A few routes have been found to restore that ductility. In the case of bonded ultra-high-performance concrete (UHPC), both cracking and ultimate loads are increased, while under rapid loading conditions, UHPFRC jacketing has an advantage [4]–[6]. Internal FRP bars and externally bonded sheets are used to provide tensile capacity and corrosion protection; however, bond at the interface restricts the amount of tensile capacity a beam can utilize [7], [8]. The incorporation of steel and hybrid fibres has resulted in a significant increase in the toughness of the matrix material, while recycled steel-wire mesh from industry has achieved similar benefits at a much lower material cost [3], [9], [10].

The type of reinforcement dictates the failure mode of the member: stainless and high-strength steel in UHPC beams are found to fail gradually compared with conventional steel [11]. The majority of this evidence is fragmentary and has accumulated by strengthening system. Results cannot be compared side by side because each test method is used against an unstrengthened control with the same geometry, loading rate, and concrete grade at which it was tested. Ductility is reported as a by-product of the increase in ultimate load, and for high-strength substrates, interface behavior, which determines what percentage of the increased tensile strength is available to the member, is inconsistent and rarely measured [12].

Existing reviews of this literature are narrative. They present each strengthening pathway, report the gains in the units used by the authors, and claim that all pathways are effective. As formulated, the conclusion is not falsifiable because there is no common basis to demonstrate that one route is superior to another. The field does not need another survey of techniques, but rather a normalization that allows comparison of the reported results and a forthright report on the extent of the evidence that survives this normalization. This review extracts reported outcomes from 23 studies and presents them in a standard form, expressed relative to each study's own control capacity, and defines a single index to determine whether a strengthening system has compromised the capacity of the system through reduced deformation capacity or enhanced the capacity as well. It then presents the number of studies for which the index can be calculated and considers that number a finding, not a restriction. The paper is organized as follows: the review methodology, normalization, synthesis results, and implications are presented in Section II. Section III presents the conclusions and the reporting changes they represent.

II. DISCUSSION

A. Review Methodology and Data Selection

Records were identified through the Directory of Open Access Journals (DOAJ) application programming interface, which returns an exact result count for any query and can therefore be re-executed by a reader. Three nested strings were run, each restricted to bibjson year:[2020 to 2026]:

S1 bibjson.abstract:(flexural AND beam AND concrete), returning 802 records.

S2 S1 AND strengthening, returning 156 records.

S3 S2 AND ("high strength" OR UHPC), returning 24 records.

The reference lists of retrieved articles were hand-searched for four additional studies published in subscription journals not indexed by DOAJ. A study was included if it included a numerical investigation (either experimental or experimentally validated) of flexural behavior in a beam with a compressive strength of 40 MPa or greater, compared with a control or reference specimen, and reported at least one quantitative flexural outcome. Studies of shear-dominated failure, columns, slabs, and unreinforced material specimens were excluded. The screening path is shown in Fig. 1, and each count in it is either a live query total or an exact difference between two. A standard form was used to code each of the included studies, including the number of specimens, specimen geometry, concrete grade, strengthening system, type and ratio of reinforcement, loading configuration, cracking load, ultimate load, mid-span deflection at cracking, yield, and ultimate, crack width, failure mode, interface preparation, and whether a finite element model was calibrated to the tests. If a study did not report a field, it was not estimated. That distinction carries the analysis in Section II.E.

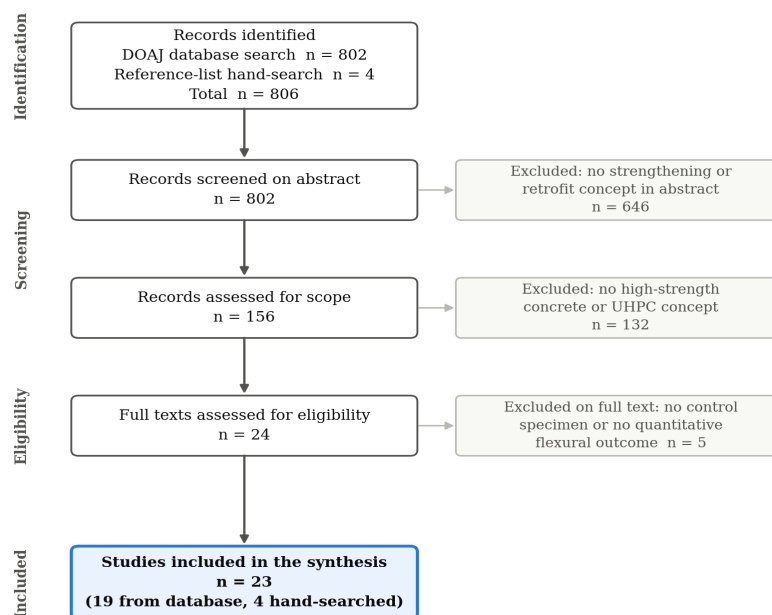


Fig.1 Screening Path Every Count is a Live DOAJ Query Total or an Exact Difference Between Two Such Totals

TABLE I EXTRACTED OUTCOMES, AS REPORTED BY EACH STUDY

S.No.	Study	Route	Specimens	Outcome as reported by the authors
1	Tao <i>et al.</i>	Matrix fibre	not stated	125 freeze-thaw cycles; 35 kg/m ³ steel + 1.5 kg/m ³ PP retained 94.5% dynamic modulus, 1.42% mass loss, 41% better than unreinforced
2	Yuan <i>et al.</i>	Cementitious jacket	not stated	Flexural strength +8% bottom jacket, +29% three-side, +40% four-side; interface bond 14-21 MPa at 28 d; high roughness ~27% above low
3	Shi & Gao	Matrix fibre	11	Fibre volume 0-2%, depth 200-350 mm, C60-C80; cracking and ultimate loads both rose with fibre fraction; mean test/predicted 1.01
4	Mirdan & Saleh	UHPC overlay	7	Stiffness +20-132%; bars across the construction joint added 17.15-41.1 kN; no interface separation observed
5	Wang & Li	UHPC overlay	not stated	Cracking load +145.2%, ultimate load +67.9%; crack distribution more uniform; DIC plus calibrated FE
6	Yoo <i>et al.</i>	UHPC overlay	not stated	Flexural strength +6% at 1.5% fibre volume; up to 7% lower deflection under impact; three steel fibre types
7	Najaf <i>et al.</i>	FRP external	25 models	Prestressed FRP +5.4 to +26.4% over internally reinforced; lateral strain down to 12.5%; 45 deg installation angle optimal
8	Muhammad & Ahmed	FRP internal	12	2400 x 250 x 180 mm; concrete 36, 73, 84 MPa; GFRP ratio 0.39-1.19%; high-strength concrete raised failure load up to 28%
9	Alshannag <i>et al.</i>	Matrix fibre	not stated	0.5% steel (60 mm) + 0.25% crimped PP gave ~18% in capacity and toughness; hybrid with recycled plastic ~6% above all-steel
10	Li <i>et al.</i>	Recycled mesh	4 modelled	Ultimate capacity increased and crack width decreased (magnitudes not stated); FE deviation within 10%
11	Li & Aoude	Reinforcement grade	3	Grade 690 bars +47% resistance with bar rupture; Grade 520 stainless +75% ductility with no capacity gain
12	Zhang <i>et al.</i>	Interface	108 tests	72 pull-off, 36 bi-shear; six surface treatments; tensile bond linear with Ra 0.29-0.96, shear response non-linear
13	Attia <i>et al.</i>	FRP external	not stated	NSM steel plate +36.64% peak load with deflection at peak 21.12% lower; GFRP highest toughness 1099.2 kN.mm, +40.25%
14	Xia	Composite action	not stated	690 MPa steel with 140 MPa UHPFRC; headed studs at 150 mm developed the critical elastic moment resistance
15	Hasan <i>et al.</i>	FRP internal	not stated	Higher limiting deflection with brittle failure at ultimate; no numerical values retrievable from the accessible record
16	Lin <i>et al.</i>	FRP external	11	Hybrid FRP raised capacity up to 30.2%; 45 deg fibre angle added 4.5%; average ductility loss 42%
17	Gong <i>et al.</i>	FRP external	not stated	Gradual prestress +35.48% capacity, ductility more than doubled; under fatigue failure moved from cover separation to bar fracture
18	Moy & Revanna	TRM	7	Basalt TRM +8.3-30.3%, carbon TRM +14.2-32.3%; five-layer U-wrap best; normal-strength substrate
19	Accornero <i>et al.</i>	Analytical	n/a	Stable versus unstable post-cracking governed by fibre volume and geometry; calibration mostly below 60 MPa
20	Shen <i>et al.</i>	Numerical	not stated	Compression yielding blocks shift failure from brittle crushing to ductile yielding, raising capacity and ductility; no magnitudes stated
21	Saadi <i>et al.</i>	Recycled aggregate	15	RCA 0-100%, a/d 1.5-3.5, concrete 55-67 MPa; 75% RCA carried 35.7% more than control, reaching 198.4 kN
22	Tian <i>et al.</i>	Fatigue	not stated	Flexural fatigue strength fell 15.0% at -10 C and 12.7% at -20 C relative to 20 C
23	Megahed	Data-driven	134 compiled	Six algorithms against ACI 440.11-22; Gaussian process regression mean R ² near 1.0, test MAPE 11.51%; 26 test points

B. Normalisation and the Trade-Off Index

Because geometry, span, and concrete grade differ across studies, absolute loads are not comparable. Each outcome is therefore expressed relative to the study's own control specimen. The capacity gain ratio is

$$CGR = (P_{u,s} - P_{u,c}) / P_{u,c}$$

where $P_{u,s}$ and $P_{u,c}$ are the ultimate loads of the strengthened and control specimens. Deformation capacity is expressed through the displacement ductility index, $DI = D_u / D_y$,

formed from the mid-span deflections at first yield and at ultimate, and its retention

$$DRR = DI_s / DI_c$$

A DRR above unity means the strengthened member deforms further before failure than its control; below unity means it fails earlier. The observation running through the literature is that capacity and ductility move in opposite directions under most strengthening systems, but no published index expresses that trade-off as a single quantity. This review defines

$$STI = (1 + CGR) \times DRR - 1$$

which is the fractional change in the product of ultimate load and ductility index, a proxy for the energy the member absorbs before failure. A system that raises capacity while preserving ductility scores above zero; a system that raises capacity by consuming ductility scores below its own CGR, and one that raises capacity by 30% while halving ductility scores negative. The index is zero when the gain in load exactly offsets the loss in deformation capacity. Each study was additionally coded in binary form against eight outcome categories: cracking load, ultimate load, deflection at yield, deflection at ultimate, ductility measure, crack width, failure mode, and interface characterisation. Where a study reported a range of gains across configurations, the maximum was taken, so reported CGR values are upper bounds.

C. Characteristics of the Included Studies

There are a total of 23 studies in the synthesis. There are 12 experimental beam studies, four numerical or analytical studies, three involving testing combined with finite element calibration, two material-level durability or fatigue studies, one that characterizes an interface, and one machine-learning study based on an existing specimen database. Counts of specimens are given where available (between 3 and 15 beams). The findings of each study are reported in Table I, as quoted by the authors of each study. The spread of designs is itself informative. No two studies in the set share a specimen geometry, a loading configuration, and a concrete grade, so

no pair can be compared without the normalisation of Section II.B. This is the fragmentation named in Section I, now counted rather than asserted.

D. Normalised Capacity Gain Across Routes

Of the 23 studies, 13 report capacity changes against their own controls in a format that can be used to calculate CGR. They are displayed in Figure.2 by strengthening route. The mean gain is 31.0% and the median is 32.3%, across a range of 0.0% to 67.9%. Two features stand out. First, the distribution is tight. Six of the thirteen values fall between 26.4% and 36.6%, and they come from four different routes: near-surface-mounted CFRP [7], GFRP bars in high-strength concrete [8], recycled concrete aggregate with CFRP [21], and carbon textile-reinforced mortar [18]. The mechanics of the materials, their costs, and failure planes are all starting to come in about 33 percent shorter. Thus, it is not correct to choose one or the other based on capacity alone because you are picking on noise.

Second, the two extremes are not the two best and worst systems. The highest value, 67.9% from a reinforced UHPC layer [5], sits alongside the lowest, 6.0% from a UHPFRC layer at 1.5% fibre volume [6], within the same route. Route membership explains little. The summary for this route is shown in Table II, and the range of values within the route is larger than the range between routes in each case in which more than one study contributes to the summary.

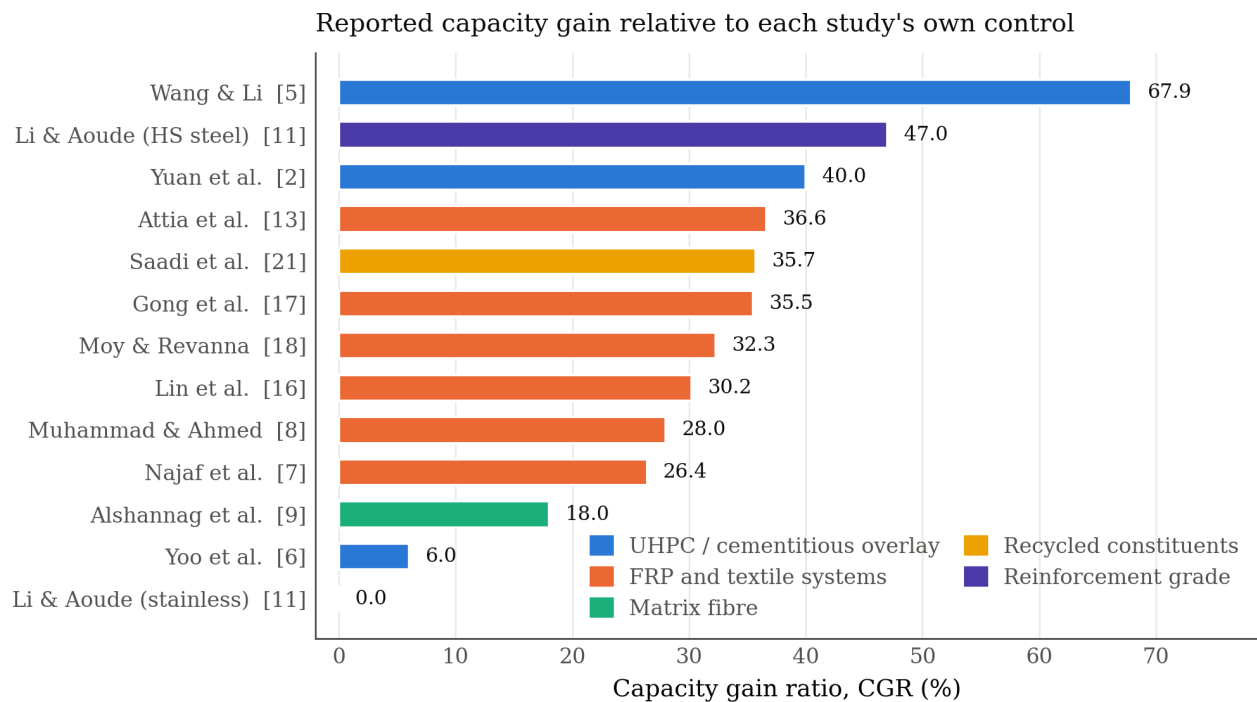


Fig.2 Capacity Gain Ratio for the 13 Studies Reporting a Change Against their Own Control. Six of the 13 Fall Between 26.4% and 36.6% Despite Belonging to Four Different Routes

TABLE II NORMALISED CAPACITY GAIN BY STRENGTHENING ROUTE

Strengthening route	Studies with CGR	Mean CGR (%)	Range (%)	Studies with DRR	Studies with STI
UHPC and cementitious overlay	3	38.0	6.0 to 67.9	0	0
FRP and textile systems	6	31.5	26.4 to 36.6	2	2
Matrix fibre	1	18.0	18.0	0	0
Recycled constituents	1	35.7	35.7	0	0
Reinforcement grade	2	23.5	0.0 to 47.0	1	1
All routes	13	31.0	0.0 to 67.9	3	3

E. Evidence Coverage and the Reporting Asymmetry

Each study is coded for the eight flexural outcomes in Fig. 3. Seventeen of 23 report ultimate load. Fewer than 30% report any other outcome. Studies reporting other outcomes include ductility measures of any kind (6 studies), failure mode (5 studies), deflection at ultimate (4 studies), interface characterization (4 studies), cracking load (2 studies), and crack width (2 studies). No records of deflection at yield are available, although this quantity is the denominator used by a displacement ductility index. The pattern is not a random omission. Ultimate load is the outcome that makes a strengthening system look successful, and it is the outcome

the field reports. The outcomes that would show what the system costs are the outcomes that go unreported. This asymmetry is the mechanism behind the comparability gap: the literature is not merely inconsistent; it is consistently informative about benefit and consistently silent about price.

The consequence is direct. Of 23 studies, 13 supply CGR and 3 supply DRR. The intersection, the set from which the trade-off between capacity and ductility can be computed at all, contains three studies. A field with several hundred tested beams across two decades yields three points on the plane that matters.

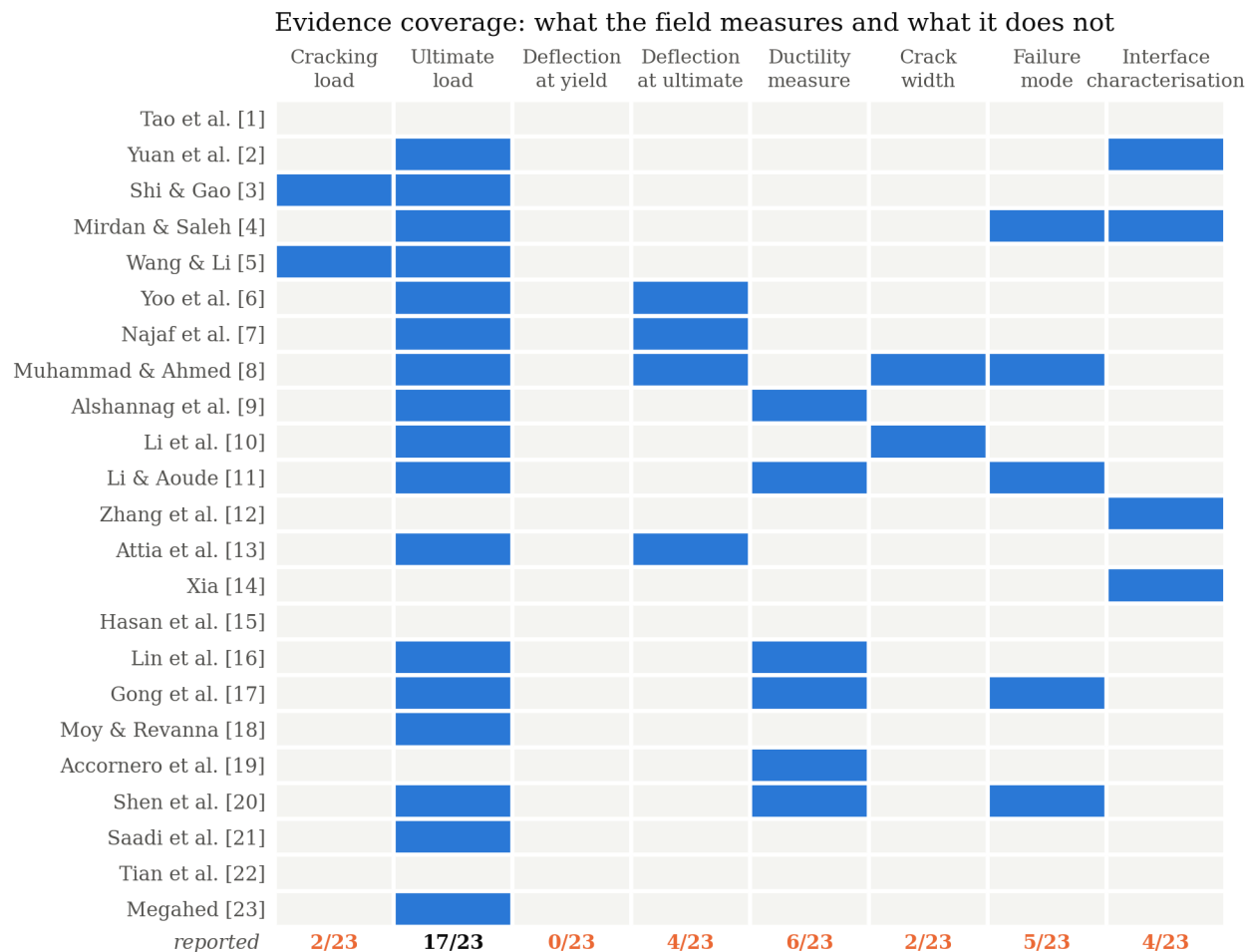


Fig.3 Evidence Coverage Across Eight Flexural Outcomes. Filled Cells Indicate the Outcome was Found in the Accessible Record

F. The Strength-Ductility Plane

Figure 4 places those three studies on the CGR-DRR plane, with iso-lines of the trade-off index. The ten studies that report a capacity change without a ductility measure appear as ticks on the lower strip, positioned by CGR alone because their vertical coordinate is unknown.

The three computable points separate almost completely from their capacity ranking. Lin *et al.* [16] and Gong *et al.* [17] report capacity gains five percentage points apart, 30.2% and 35.48%, which makes them near neighbours in Figure 2. Their trade-off indices are -0.245 and +1.710. Lin's hybrid FRP sheets increased capacity but reduced deformation capacity by 42%, resulting in a decrease in capacity and deformation capacity: the capacity of the strengthened member was higher, and the warning was lower than that of the member being strengthened. Gong's gradually prestressed CFRP increased its capacity by a similar amount, and its index is more than doubled in the set.

The third point makes the same argument from the opposite direction. Stainless reinforcement in the UHPC beams of Li and Aoude [11] raised ductility by 75% without raising capacity at all. Ranked on CGR, it is last of the thirteen in Figure 2, at zero. It is ranked second of three on STI, at +0.750, ahead of all the systems that can be evaluated for the trade-off by capacity ranking. The same study's Grade 690 bars provided 47% more resistance and recorded the third-largest capacity gain in the entire set; however, with a ductility loss that the study describes but does not quantify, the bars failed by rupture due to limited strain capacity. Both configurations are from a single test programme and rank capacity in the reverse order to performance in the test programme. Table III gives the ranking.

Three points cannot support a regression, and none is attempted. What they support is a weaker but sufficient claim: within the only sample where both quantities are known, capacity gain does not predict net performance, and in one case of three it points the wrong way entirely.

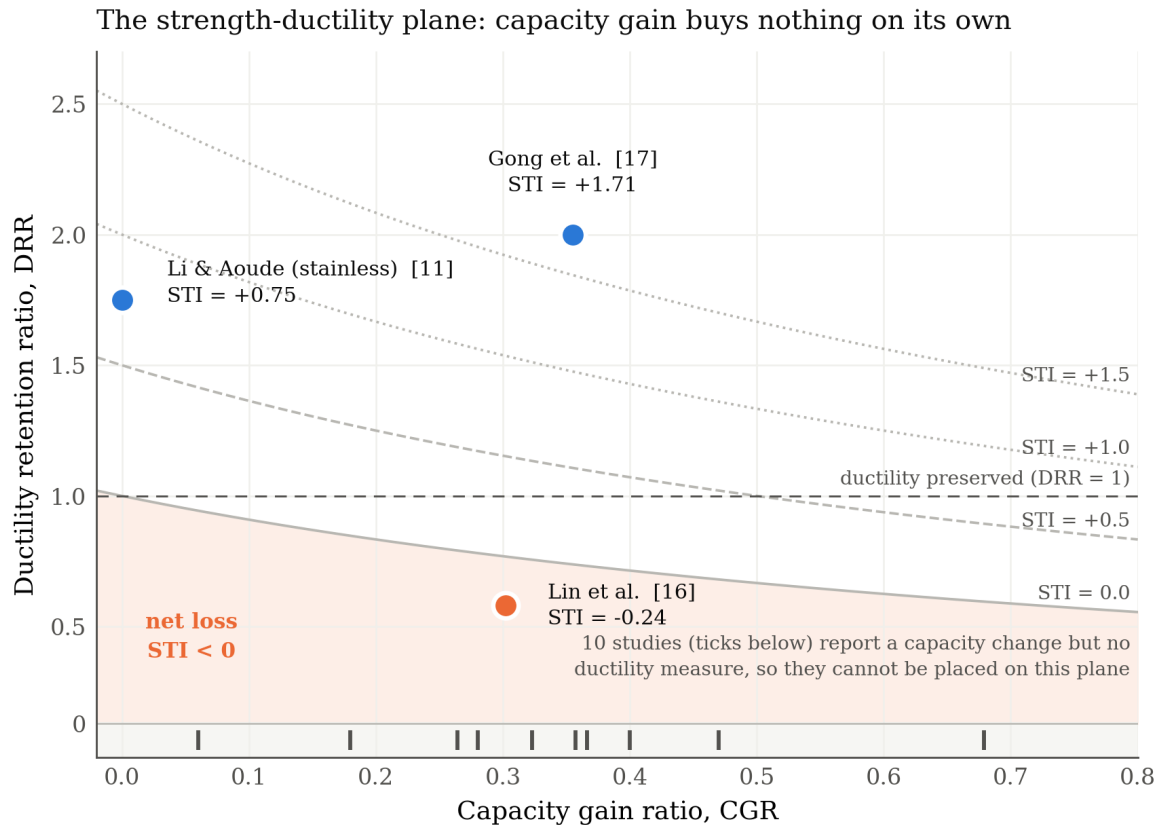


Fig.4 The strength-ductility Plane. Curves are Iso-Lines of the Trade-Off Index. Ticks on the Lower Strip Mark the 10 Studies Reporting a Capacity Change with no Ductility Measure

TABLE III THE THREE STUDIES PERMITTING A TRADE-OFF CALCULATION, RANKED BY STI

Rank by STI	Ref	System	CGR	DRR	STI	Rank by CGR alone
1	[17]	Gradually prestressed NSM CFRP	+0.355	2.00	+1.710	2 of 3
2	[11]	Stainless reinforcement in UHPC	0.000	1.75	+0.750	3 of 3
3	[16]	Hybrid FRP sheets	+0.302	0.58	-0.245	1 of 3

G. Interface Characterisation as a Parallel Blind Spot

The same asymmetry appears in how overlay systems are reported. Zhang *et al.* [12] ran 72 pull-off and 36 bi-shear tests across six surface treatments and two substrate strengths and found interfacial tensile strength rising linearly with mean roughness over $R_a = 0.29$ to 0.96 , while shear response did not follow the same trend. The one parameter that most overlay studies report is mean roughness, but that is not a parameter that describes shear transfer. Four of 23 studies characterize the interface at all. In overlay systems, all capacity gain is passed through this joint, and the dense, low-permeability HSC substrate is more difficult to bond than standard concrete; this represents the same gap as for ductility. The largest reported capacity gain in the whole synthesis, 145.2% in cracking load from a reinforced UHPC layer [5], rests on an interface whose governing mechanism the field does not routinely measure.

H. Implications for Reporting and Design

There are two implications here for practice. When choosing to strengthen or upgrade systems designed for published capacity increases, the designer is selecting the wrong metric with regard to safety in seismic and impact conditions, as described in Figure 4. If no ductility measure is available, it may be best to say that the net effect of the system is uncertain rather than that it is beneficial merely because it has a proportional capacity gain.

For reporting, the requirement is small. Specimens that were previously instrumented with linear variable differential transformers would shift into the plane if deflection were recorded from the yield point to ultimate. This is because 10 of the studies in this set lacked one measured quantity needed

for comparison. Based on the evidence in Figure 3, the number of samples available for a flexural strengthening paper reporting deflection at first yield would be quadrupled if the same samples also reported ultimate load. The second gap can be closed with a corresponding requirement for overlay studies to prepare interfaces and characterize shear.

I. A Minimum Reporting Set for Flexural Strengthening Studies

The diagnosis in Sections II.E and II.G implies a prescription. When there is no convention that requires ductility and interface behavior, the solution is a convention. Table IV indicates a minimum set of nine reporting items, each of which is linked to a comparison it allows and to the percentage of the current sample that already reports it. The items are not new measures. Six of the nine are already recorded in a standard 4-point bending test on an instrumented specimen and are just not carried into the published paper.

The distinction that matters here is between measuring and reporting. All studies included in this synthesis that used a linear variable differential transformer at mid-span had a continuous load-deflection curve, from which deflection at first yield and deflection at ultimate could be read. The quantities are not included in the published papers but are included in the laboratory records of the studies. The cost of the proposed set is thus not experimental but editorial - the marginal-cost column of Table IV records this: six items would cost nothing beyond a table row, one requires a table that is already used by several completed studies based on crack microscopy or digital image correlation, and two require a specimen with interfaces that should be cast anyway, as they are overlay studies.

TABLE IV PROPOSED MINIMUM REPORTING SET FOR FLEXURAL STRENGTHENING STUDIES

S.No.	Reporting item	Comparison it enables	Supplied by	Marginal cost to the experimenter
1	Ultimate load of strengthened and control specimens	Capacity gain ratio, CGR	17 of 23	None; already the headline result
2	Cracking load of both specimens	Cracking gain ratio, serviceability onset	2 of 23	None; present in the recorded load trace
3	Mid-span deflection at first yield	Denominator of the ductility index	0 of 23	None; read from the LVDT trace already captured
4	Mid-span deflection at ultimate	Numerator of the ductility index	4 of 23	None; read from the same trace
5	Ductility index or the deflections forming it	Ductility retention ratio and trade-off index	6 of 23	None; computed from items 3 and 4
6	Crack width at a stated service load	Serviceability comparison across systems	2 of 23	Crack microscope or DIC, already used by several studies
7	Failure mode, classified	Separates ductile from brittle capacity gains	5 of 23	None; observational
8	Interface preparation and mean roughness	Bond assessment for overlay systems	4 of 23	Profilometer or sand-patch test
9	Interface shear characterisation	Shear transfer, which roughness alone does not predict	see item 8	Bi-shear or slant-shear companion specimens

Figure 5 represents the value that would be recovered if the reporting set were adopted. Under current practice, the trade-off index can be computed for three of the 23 studies. Four

additional studies already report deflection at ultimate, and only three more would be needed for deflection at yield. A requirement for both deflections would make all the studies

reporting a capacity gain comparable, bringing the sample to thirteen, which is four times the number of studies currently in use without casting a single additional beam. The other 10 studies are analytical, material-level, or interface investigations and do not have a beam-level capacity gain.

A reporting convention of this kind is unusual in structural materials research but not without precedent in adjacent

fields, where minimum data sets are enforced at submission. The barrier here is not technical difficulty. It is that ultimate load alone has been sufficient for publication, and the quantities that would expose what a strengthening system costs have never been required. Table IV is offered as a starting point, not as a final standard, and the coverage column offers editors a measure of uptake.

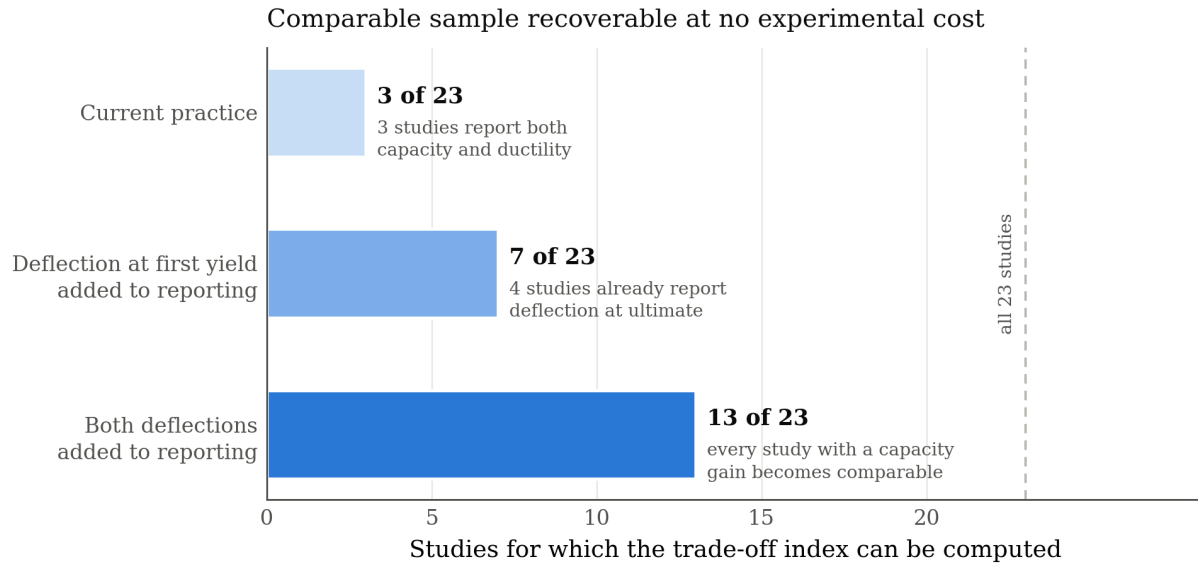


Fig.5 Studies for which the Trade-off Index Becomes Computable Under Progressive Adoption of the Reporting Items in Table IV. No Additional Specimens are Required at any Tier

J. Limitations of the Synthesis

Three limitations bound these results. The abstracts and open-access full texts were extracted, while a few full texts were behind subscriptions. A coded absence in Figure 3 does not mean that the study did not include the outcome, but rather that it was not found in the accessible full text. The coverage figures should be read as a lower bound on what the field reports, and every cell requires verification against the full text before the reporting-gap claim is treated as final. Second, screening was done using nested database queries, not by two independent reviewers. It is also exactly reproducible, unlike manual screening; however, it is based on abstract vocabulary, not on reading, and a study that does not include the word strengthening in its abstract but reports a strengthened beam would be overlooked. Third, the maximum gain in a study was reported, so the mean CGR of 31.0% is an upper bound; control specimens were not standardised between studies, so a gain normalized against a weak control is not the same as a gain normalized against a strong control. This is a natural process of secondary synthesis and is why pooling is not recommended.

III. CONCLUSION

This review compared 23 published flexural studies of high-strength concrete beams on a common basis and determined the sum total of the evidence. Thirteen studies report capacity

changes against a control. They have a mean capacity gain of 31.0%, and six of the thirteen are within 10 percentage points of each other despite the four different strengthening routes, meaning that capacity gain does not discriminate between systems with different mechanisms, costs, and failure paths. The trade-off index used here discriminates where capacity gain does not, but it can be assessed for just three of the 23 studies. Within that sample, it reorders them. The hybrid FRP sheets have the highest capacity with the lowest index at -0.245, as a 42% reduction in ductility was required for the 30.2% increase in capacity. Stainless reinforcement has the lowest capacity, at 0, and the second-lowest score on the index, at +0.750. Both are exceeded by prestressed CFRP, which has an index of +1.710, more than twice that of the second system. The term capacity gain does not produce the same rankings as net performance, and in one of three cases they are antagonistic. The reason the sample is three and not 23 is the review's second finding. Ultimate load is reported by 17 of 23 studies; no other outcome is reported by more than six, and deflection at yield, which a ductility index requires, appears in none of the accessible records. Interface characterization shows the same asymmetry, appearing in four studies while overlay systems transfer their entire capacity gain through that joint. Two recommendations follow. For flexural strengthening studies, deflection at first yield should be included with ultimate load, which would make ten more studies in this set comparable without requiring any experiments. Overlay studies should include

interface preparation and shear characterization, as mean roughness is insufficient to predict shear transfer. Until both become routine, the choice between strengthening systems for higher-strength concrete beams is inconsequential to this synthesis because it does not provide any information about what will happen that affects safety.

Declaration of Conflicting Interests

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The authors confirm that no AI-assisted technologies were used in the preparation or writing of the manuscript, and no images were altered using AI.

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